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Applications of Ground-Based Remote Sensing Techniques

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The development of selected techniques for the remote measurement of winds, shear, turbulence, aerosols, and temperature and moisture profiles has been outlined in some detail. Emphasis has been placed on techniques that may provide high-resolution data in the vicinity of airbases. A representative and fairly extensive list of references to the evolution of the various techniques has been prepared. The FM-CW radar and CO_2 pulse Doppler laser have been identified as valuable for low-level wind and shear measurements. Strong downdraft conditions may be identified through use of infrared

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20. Abstract (Continued)

thermal anomaly detectors. Temperature and moisture profiles may be obtained through a combination of active sounding for profile inflection points and thermal or microwave multichannel radiometry.

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Applications of Ground-Based Remote Sensing Techniques

1. INTRODUCTION

The Air Weather Service desires improved methods of obtaining high-resolution measurements of wind speed and direction, wind shear, gusts and turbulence, and temperature and moisture profiles through the lower atmosphere. For a number of years, extensive development efforts have been in progress to improve satellite instrumentation and data interpretation for remote sensing of most of the above-mentioned parameters. The techniques developed provide valuable insight into the physical and mathematical difficulties associated with remote sensing.

The present study has been limited to a review of techniques that might be applied to improve ground-based detailed measurements in the vicinity of airbases. Available technology of potential value includes pulse and FM-CW Doppler radars, laser Doppler backscatter and crossbeam correlators, laser Raman frequency-shifted molecular cross section measurements, multifrequency (DIAL) laser and passive radiometer differential absorption measurements, optical turbulence sensing, and acoustic sounders.

During the last two decades, several agencies have conducted in-house or sponsored research using these concepts. The work is continuing at research levels of effort on the more promising technology, and has results in considerable understanding of the utility and limitations of the systems in application to specific problems.

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This report briefly discusses salient features of the technology, and recommends placing emphasis on the further development of a CO_2 laser Doppler system for measurements of wind, wind shear, and aircraft wake vortices in the approach/departure regions of airfields. The recommendation is based on the desirability of obtaining a hazardous condition sensor that can operate down to very low elevation angles in an airfield environment. A sensor of this nature will also provide a capability for extending radar Doppler measurements of thunderstorm flow out into the clear air environment of the storm, so that interactions of the storm and its surroundings may be traced and the development of hazardous features such as gust fronts and downdrafts may be followed with great resolution.

2. LASER ATMOSPHERIC PROBING

A variety of new techniques for atmospheric measurements have been developed following the practical realization of high-intensity coherent light sources. Potential applications were discussed by Goyer and Watson.[1] They stressed that the coherence properties available with a laser beam were of utmost importance for extending the use of optical probing of atmospheric properties. A spatially coherent beam will have a uniform phase wavefront. The coherence length, or distance the wave can travel before phase degradation, is related to the narrowness of the transmitted signal frequency bandwidth. Laser interferometer experiments can therefore be conducted over much greater distances than are possible with conventional light sources. Since atmospheric molecules and aerosols scatter energy from the beam, the Doppler frequency-shifted scattered signal provides a wide noise-like received spectrum in comparison with the transmitted spectrum. The backscatter signal can be analyzed for wind and turbulence information in accordance with the relation $\Delta f = 2V_r/\lambda$, where λ is the laser wavelength and V_r is the average radial wind component associated with a mean frequency shift of Δf.

A distinction between radar and laser Doppler measurements is that the Doppler spectrum width exceeds the laser transmitted pulse spectrum. This permits single-pulse Doppler wind estimates to be made with laser systems. Resolution will depend upon the frequency shift or "chirp" during the pulse. Backscatter targets are always available in the atmosphere. The attainable range is determined by the nature of the laser system. In contrast, a Doppler radar system is generally constrained to operate on precipitation-sized particles to provide a signal sufficient for Doppler frequency analysis. Frequency shifts for moving targets

1. Goyer, G. and Watson, R. (1963) The laser and its application to meteorology, Bull. Amer. Meteorol. Soc. 44:564-570.

scale are $\lambda_{radar}/\lambda_{laser}$ or a factor of 10^4 for 10 μm CO_2 lasers as compared with 10 cm radar. Research radars have been able to sense clear air refractive index differences occurring on a size scale reflecting energy at the radar half-wavelength. These patches generally are considered to follow the wind patterns, and also can be used for wind sensing. Care must be taken to avoid interpreting the signal scattered from flying insects as a passive target return.

Early atmospheric measurements with lasers were primarily concerned with interpretation of the backscatter power signal to provide estimates of stability layer locations and aerosol concentration. These efforts are reviewed in some detail in Section 2.1. More complex studies have been conducted to sense molecular concentrations of water vapor and of various air pollution chemicals. Receiver frequency offset filtering has been used to measure the Raman scattered signal. The frequency offset selected is specific for the particular molecule of interest, and the received intensity is proportional to the species concentration. Raman scattering cross sections are very small in comparison with normal backscatter from molecules, so powerful sources and large receiving telescopes are required for these measurements. Signal integrating and processing techniques also must be more elaborate. A detailed review of Raman measurements was provided by Inaba.[2]

Applications of Raman scattering to measurement of the absolute water vapor profile in the lowest few kilometers were worked out by Cooney, in a series of papers.[3,4,5] A frequency-doubled ruby laser was used to transmit on 347.15 nm. The Raman scattered energy is shifted from the incident radiation by an amount corresponding to particular energy level differences in the vibrational/rotational spectrum of the molecule. Filtered receiver channels centered on 377.7 nm for the N_2 molecule and centered on 397.6 nm for the H_2O molecule were used. The ratio of the H_2O channel power received to that of the N_2 power is proportional to the water vapor mixing ratio. If a standard atmosphere N_2 concentration as a function of height is assumed, the absolute humidity profile can be estimated with high resolution.

Accurate laser system and molecular scatter cross section calibrations are required for these measurements. The addition of a high common-mode rejection

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2. Inaba, H. (1976) Detection of atoms and molecules by Raman scattering and resonance fluorescence, in Laser Monitoring of the Atmosphere ed. E. D. Hinkley, Springer-Verlag, Berlin, Heidelberg, New York: 153-236.

3. Cooney, J. (1970) Remote measurements of atmospheric water vapor profiles using the Raman component of laser backscatter, J. Appl. Meteorol. **9**: 182-184.

4. Cooney, J. (1971) Comparisons of Water vapor profiles obtained by radiosonde and laser backscatter, J. Appl. Meteorol. **10**:301-308.

5. Cooney, J. (1973) A method for extending the use of Raman lidar to daytime, J. Appl. Meteorol. **12**:888-890.

differential amplifier in the two receiving channels was believed to allow for an extension of the technique to daytime operation. The normal light intensity received was from 100 to 1000 times the signals associated with the Raman scatter, so a high degree of rejection was required.

Recent French experience with the technique has been reported by Pourny, Renaut, and Orszag.[6] They found general agreement between laser and radiosonde measurement of mixing ratio profiles in the lowest 2 km, and indicated several system improvements that would result in more accurate results. Vertical resolution of 30 m was obtained and relative accuracy of 15 percent at 1 km was found in their experiments. At present, these Raman techniques are considered to be too complex for routine application to AWS problems.

A concept of potential value is the use of a dual or multifrequency laser system to determine the differential absorption of molecular constituents. Schotland[7,8] developed this technique to obtain water vapor profiles in the lowest few kilometers of the atmosphere. In this experiment, one frequency is selected for maximum absorption by the molecule of interest, and another nearby much less absorbing frequency is used to provide backscatter suppression. The received differences in signal intensities are primarily due to the absorption associated with the molecular species concentration, thus the density can be estimated as a function of range. Analysis of the returned signal at the two frequencies can be interpreted as species concentration through the equation

$$\ln(P_{T1}/P_{T2}) - \ln(P_{R1}/P_{R2}) \cong 2K(\lambda) \int_0^R \rho(R)\, dR \qquad (1)$$

where the subscripts 1, 2 represent a wavelength centered on the line center absorption maximum and out in a wing of the absorption spectrum respectively, and K represents the species volume absorption coefficient. Thus, from measurements of the transmitted and received power ratios, it is possible to estimate the water vapor density, ρ, as a function of range. Possible errors associated

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6. Pourney, J.C., Renaut, D., and Orszag, A. (1979) Raman-lidar humidity soundings of the atmospheric boundary-layer, Appl. Optics 18:1141-1148.

7. Schotland, R.M. (1964) The determination of the vertical profile of atmospheric gases by means of a ground based optical radar, Proc. 3rd Symposium on Remote Sensing of the Environment, 14-16 Oct 1964, Univ. of Michigan, Ann Arbor, Mich., 215-224.

8. Schotland, R.M. (1966) Some observations of the vertical profile of water vapor by means of a laser optical radar, Proc. 4th Symposium on Remote Sensing of Environment, 12-14 Apr 1966, Univ. of Michigan, Ann Arbor, Mich., 273-277.

with utilization of the technique were described by Schotland.[9] In the lower atmosphere, these are primarily related to variations in the frequency stability of the laser used at the two frequencies, and to possible variations in backscatter associated with time fluctuations of aerosol concentration if the two frequencies are transmitted sequentially.

This differential absorption technique has been greatly expanded in recent years in the general field of pollution and trace gas remote monitoring. It is a powerful method that could be applied to a number of toxic pollution monitoring problems of the Air Force, as well as to the water vapor profiling problem. A detailed review has been provided by Hinkley, Ku, and Kelley.[10]

2.1 Laser Return Power Measurements and Interpretation

The power received in laser atmospheric measurements can be expressed by an equation similar to the radar equation. Collis[11] formulated it as

$$P_\lambda(R) = \eta \frac{C J_\lambda A \beta_\lambda(R)}{2R^2} \exp\left[-2 \int_0^R \alpha_\lambda \, dR\right] \qquad (2)$$

where η is a system efficiency factor; C the velocity of light; J_λ the transmitted energy; A the effective optical receiver area; β_λ the 180° volume backscatter coefficient; R the range; α_λ the volume extinction coefficient containing terms for scattering and for absorption effects; and λ the wavelength of radiation in use. The formulation applies to single scattering conditions.

One notes that the two atmospheric parameters α and β are intermingled in the returned power signal. Numerous studies have been conducted to interpret the resulting signal. Theoretical relationships between α and β can be obtained through various formulations and extensions of the Mie scattering theory in terms of particle shapes and nature of the size distributions of scatterers, and of the estimated refractive and absorption indices of the particles.

A direct interpretation of the backscattered power can be used to estimate locations of features such as inversions, stable layers, or cloud boundaries. If α and β are regarded as range independent, Eq. (2) can be differentiated to provide

9. Schotland, R.M. (1974) Errors in the lidar measurement of atmospheric gases by differential absorption, J. Appl. Meteorol. 13:71-77.

10. Hinkley, E.D., Ku, R.T., and Kelley, P.L. (1976) Techniques for detection of molecular pollutants by absorption of laser radiation, Laser Monitoring of the Atmosphere, ed. E.D. Hinkley, Springer-Verlag, Berlin, Heidelberg, New York, 237-295.

11. Collis, R.T.H. (1966) Lidar: a new atmospheric probe, Quart. J. Roy. Meteorol. Soc. 92:220-230.

an estimate of the extinction coefficient α. That is,

$$\alpha = - d\ln[R^2P(R)]/2dR \quad . \tag{3}$$

Estimates of the extinction coefficient can be directly applied to visibility problems. Koschmieder[12] determined a threshold ratio or contrast of luminosity ε associated with a visual range V at which a black object's apparent luminosity can be distinguished against the horizon sky background luminosity. The value of ε may be taken in the range from about 0.02 to about 0.06 for various targets and applications. This ratio can be expressed in terms of the extinction coefficient as

$$\varepsilon = e^{-\alpha V} \quad \text{or} \quad V = -\ln \varepsilon/\alpha \quad . \tag{4}$$

A concise discussion of visibility theory is available in the Smithsonian Meteorological Tables.[13] Comprehensive information is provided by Middleton.[14]

It may be possible to make quantitative estimates of visual range from analysis of the range-corrected backscatter laser signal in accordance with the above equations. Some estimates obtained with lasers have been compared with controlled visual range observations. Pueschell and Noil[15] discussed relations between visibility and measured aerosol concentrations and size distributions. Mie calculations were combined with the experimental aerosol data to determine theoretical visual range V_c. The ratio V_c/V_o, where V_o was the observed range, appeared to resemble a Gaussian distribution peaked at a ratio of one. Values for this limited test ranged from 0.16 to 1.52. The best agreement was found with stable meteorological conditions. With marine aerosol present, the visibility was usually less than calculated; the opposite was found with industrial pollution in the area. They believed that short-period fluctuations in aerosol concentration were important factors in the causing of errors in visibility determination, and that these fluctuations could best be monitored by direct instrumental measurement of the scattering and extinction. The laser provides an excellent basis for such measurements.

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12. Koschmieder, H. (1924) Theorie der horizontalen sichtweite, Beitr. Phys. Frei. Atmos. 12:35-55 and 171-181.

13. Smithsonian Meteorological Tables, 6th Ed., ed. R.J. List, Smithsonian Institution, Wash., D.C., 527 pp.

14. Middleton, W.E.K (1958) Vision Through the Atmosphere, Univ. of Toronto Press, 246 pp.

15. Pueschell, R.F. and Noll, K.E. (1967) Visibility and aerosol size frequency distribution, J. Appl. Meteorol. 6:1045-1052.

One of the earliest experiments in applying the laser to visibility and air pollution problems was conducted by Barrett and Ben-Dov.[16] They used Mie scattering theory calculations to deduce turbidity, visibility, and particulate concentrations as a function of altitude to about 2 km. They also found a solution for the integral equation contained in the laser equation for conditions when attenuation was important.

Fernald, Herman, and Reagan[17] extended this work by pointing out an improved technique for evaluating the integral equation. An important feature is that the ratio of the volume extinction coefficient α to backscatter coefficient β generally will remain nearly constant with range, since aerosol composition and size distribution at a specific time is normally uniform in a well-mixed layer of the lower atmosphere. This, coupled with some independent measurement of the total path transmittance (for example, with a solar radiometer), will permit a more accurate iterative evaluation of the equation. They found it desirable to include molecular extinction and backscatter in the calculation and that a good method for laser system calibration is to analyze the return power signal received in very clear air conditions in terms of the well known properties of Rayleigh scattering from atmospheric molecules. Reasonable solutions to the integral equation for aerosol concentration as a function of range were found to depend on having a sufficiently turbid atmosphere so that the aerosol signal could override the molecular and system noise contributions.

A more powerful technique for remote aerosol measurement was discussed by Zuyev et al.[18] They used multiwavelength laser backscatter as input data for determination of particle size distributions as found by inversion of the equation

$$\beta(\lambda) = \pi \int_{r_1}^{r_2} K(r, \lambda)\, r^2\, n(r)\, dr \tag{5}$$

where $K(r, \lambda)$ is the Mie efficiency factor for backscatter and $n(r)$ is the particle size distribution. They applied the technique to conditions of low attenuation,

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16. Barrett, E.W. and Ben-Dov, O. (1967) Application of the lidar to air pollution measurements, J. Appl. Meteorol. 6:500-515.

17. Fernald, F.G., Herman, B.M., and Reagan, J.A. (1972) Determination of aerosol height distributions by lidar, J. Appl. Meteorol. 11:482-489.

18. Zuyev, V.Ye., Kozlov, N.V., Makiyenko, E.V., Naats, I.E., and Samokhvalov, I.V. (1977) Some results from multifrequency lidar sounding stratospheric aerosol microstructure, Izvestiya, Atmospheric and Oceanic Physics 13:439-443.

thus neglecting effects associated with the term α in the laser equation. An optimal-parameter solution technique was used. Calculations were based on gamma an Junge analytical representations for the n(r) distribution functions. Derived profiles and total number concentrations obtained appear to be in reasonable agreement with direct measurements. This paper contains a number of references to other Soviet work on solutions to problems of this nature.

Use of the laser equation has been extended to measurement of rainfall rate by Shipley, Eloranta, and Weinman.[19] They defined an effective atmospheric extinction coefficient during rainfall as

$$\alpha(R) = \varepsilon_r \alpha_r(R) + \varepsilon_a \alpha_a(R) \tag{6}$$

where the subscripts r and a denote rain and aerosol respectively. the ε multipliers were said to be corrections for multiple scattering effects. The factor α_a was determined from Eq. (3) as previously discussed. An iterative technique was developed to estimate the spatially inhomogeneous distribution of α_r. They found a relation

$$\alpha_r = (0.16 \pm 0.04)\, R^{0.74 \pm 0.12} \tag{7}$$

where in this equation R is rainfall rate in mm/hr and α_r is km^{-1}. Some penetration of the rain sheets was obtained with a nominal 1 Joule ruby laser. They estimated a 5 km operating range with rates of 10 mm/hr and a 1 km range at a heavy shower rate of 100 mm/hr.

Advantages of extending the techniques to infrared wavelengths have been pointed out by Chýlek, Kiehl, and Ko.[20] Analysis of extinction theory for wavelengths similar to the largest particle size in a distribution indicates that measurements in the 9 to 12 μm infrared range will yield unambiguous interpretations of aerosol mass concentrations to within a factor of three. Similar measurements at visible wavelengths may yield concentrations that vary by a factor of 100, depending on the nature of the size distribution.

2.2 Laser Wind Measurements

The development of laser systems for fluid velocity measurements has proceeded along several lines. Laboratory and wind tunnel remote flow measurements are normally made with bistatic or multistatic laser systems, and generally rely

19. Shipley, S.T., Eloranta, E.W., and Weinman, J.A. (1974) Measurement of rainfall rates by lidar, J. Appl. Meteorol. 13:800-807.

20. Chylek, P., Kiehl, J.T., and Ko, M.K.W. (1979) Infrared extinction and the mass concentration of atmospheric aerosols, Atmos. Envir. 13:169-173.

on interpretation of a forward-scattering crossbeam interference pattern associated with the motion of small scattering particles across the beam. The technology has been extensively developed in the last 15 years. Equipment for these measurements is commercially available. It is generally restricted to path lengths of the order of meters. These systems rely on alterations of an interference fringe pattern. The pattern may be established through various beam splitter and lens arrangements. A good review was provided by Rudd.[21] Farmer, Hornkohl, and Brayton[22] have discussed situations in which these fringe pattern systems or a class of heterodyne local oscillator systems may be more useful.

Several programs have been conducted to extend a general concept of crossbeam measurements to larger distances so that crosswind components can be measured at useful atmospheric ranges. Lawrence, Ochs, and Clifford[23] indicated that patches of refractive index inhomogeneity can be identified as distinct scintillation patterns of some persistence and interpreted as a measure of crossbeam wind speeds. One analysis technique is based on Taylor's frozen turbulence hypothesis. The time between occurrence of a particular pattern at two spaced detectors is related to the wind speed. In practice, it was found that the patterns tend to decay, and it was better to analyze the slope of the observed cross correlation function of the detector outputs at zero time lag. This slope has been shown to be proportional to the mean transverse wind speed. Tests over a 1 km path indicated good agreement with the average of a network of propeller-type anemometers located along the path. It was subsequently found that in strong turbulence, leading to saturation of the scintillation patterns, a large aperture receiver would be immune to the shift in the effects of Fresnel-zone sized eddy patterns as the turbulence changed. Ochs, Clifford and Wang[24] described the theory and results of measurements using new larger receivers illuminated by an extended incoherent source. Crosswind measurements were deemed satisfactory over a 500 m range in conditions of strong integrated refractive turbulence.

A modification of the technique was discussed by Pries, et al.[25] They described a passive remote crosswind sensor that uses natural light as the source

21. Rudd, M.J. (1971) The laser anemometer—a review, Optics and Laser Technology:200-207.

22. Farmer, W.M., Hornkohl, J.O., and Brayton, D.B. (1972) A relative performance analysis of atmospheric laser Doppler velocimeter methods, Optical Engineering 11:24-30.

23. Lawrence, R.S., Ochs, G.R., and Clifford, S.F. (1972) The use of scintillations to measure average wind across a light beam, Appl. Optics 11:239-243.

24. Ochs, G.R., Clifford, S.F., and Wang, T.I. (1976) Laser wind sensing: the effects of saturation of scintillation, Appl. Optics 15:45-50.

25. Pries, T.H., Rodriguiz, R., Walters, D.L., Ochs, G.R., and Lawrence, R.S. (1977) Passive remote crosswind system, WMO Conference on Instruments and Methods of Observation, July 27-30, 1977:45-49.

rather than a remote artificial source as described above. Four apertures formed pairs of lenses to focus the scintillating light patterns onto a photo diode array. The covariance function of the pattern was calculated. The best fit time delay between this function and a theoretical covariance function was determined. This delay is proportional to the crosswind speed. The unit described had been range weighted to provide best estimates to ranges of about 200 meters.

Variations in the techniques have been developed by Bartlett and She.[26, 27] In the first, a split laser beam was crossed at the designated range of interest, thus forming an array of fringes with spacing equal to $\lambda/[2 \sin \theta/2]$ where θ is the angle between the two beam axes. A single fairly large particle crossing the fringe pattern will intensity modulate the pattern at a frequency equal to the transverse velocity divided by the fringe spacing. This modulation was detected as a backscatter signal with a telescope located near the laser transmitter. The correlation function was obtained from the return signal with a clipped digital photon correlator and interpreted as crosswind. The fringe system was thought to be useful for up to several hundred meters range with several watts of laser power. Unfortunately, the differential beam wander associated with the separated laser paths due to atmospheric refractive turbulence will limit the range of a fringe system.

Another technique they used was to transmit two nearly parallel beams closely spaced and monitor the time of flight of a single particle across the two beams from the time interval between reception of the scattered signals from the focussed beam spots. This transit-time mode of operation was believed capable of providing crosswind measurements up to about 1 km range with a 6 watt source. Since the beams were close together, atmospheric effects tended to displace both beams in similar fashion, thus preserving the relative beam separation distance to longer ranges. It was estimated that about one large particle per second would be measured at this range, thus the system had a rather low data rate. It also was limited to nighttime operation.

A technique using a 1 Joule ruby laser to provide daytime estimates of the motion of larger scale aerosol inhomogeneity patches was described by Eloranta, King, and Weinman.[28] Pairs of individual samples of the fractional deviation of the backscatter power return of an individual pulse from the average power return

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26. Bartlett, K.G., and She, C.Y. (1976) Remote measurement of wind speed using a dual beam backscatter laser Doppler velocimeter, Appl. Optics 15:1980-1983.

27. Bartlett, K.G., and She, C.Y. (1977) Single-particle correlated time-of-flight velocimeter for remote wind-speed measurement, Optics Letters 1:175-177.

28. Eloranta, E.W., King, J.M., and Weinman, J.A. (1975) The determination of wind speeds in the boundary layer by monostatic lidar, J. Appl. Meteorl. 14:1485-1489.

of a number of pulses were analyzed. Maximum correlation of the locations of significant and persistent features of the backscatter pattern as a function of time were then interpreted as radial wind components displacing the anomalous aerosol features. Best results were obtained with hazy atmospheric conditions and at heights between 500 and 1000 meters. Reasonable agreement was found between the laser wind profiles and pilot balloon wind observations.

The most reliable and longest-range remote wind measurements have been obtained with CO_2 laser system measurement of the Doppler radial velocity component. Extensive development programs were conducted in the late 1960's and early 1970's, sponsored by NASA and FAA in the United States and by the Royal Radar and Aircraft Establishments in the United Kingdom. An application of great interest was to the remote study of aircraft wake vortex structure. Huffaker, Jelalian, and Thompson[29] described a CW system for wake detection. They demonstrated that the wake associated with a DC-3 aircraft could be reliably located. Follow-on efforts were conducted at Kennedy International Airport under FAA auspices. Two scanning laser velocimeters monitored some 1600 landings in a 6 month test program. Positions of vortices were located to within 3 m. Some were tracked to about 500 m range over a time of 80 sec. Details are contained in Bilbro, et al.[30] Characteristic vortex velocity patterns and aircraft exhaust enhanced aerosol backscatter were observed and characterized for a number of types of commercial aircraft.

Much of the early systems development work in this area is described in NASA and Raytheon Co., project reports. A rather complete description and bibli ography has been prepared by Bilbro[31] for forthcoming publication in Applied Optics. Lawrence et al[32] demonstrated agreement of anemometer and CW CO_2 laser wind measurement at 30 m range, and indicated measurements had been made to 300 m. Analysis of the optical pattern of the beam-expander telescope and, assuming shot noise limited heterodyne detection, the signal to noise ratio, was found to be

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29. Huffaker, R.M., Jelalian, A., and Thomson, J.A.L. (1970) Laser-Doppler system for detection of aircraft trailing vortices, Proc. IEEE 58:322-326.

30. Bilbro, J.W., Jeffreys, H.B., Weaver, E.A., Huffacker, R.M., Craig, G.D., George, R.W., and Marrero, P.J. (1976) Laser Doppler velocimeter wake vortex tests, FAA-RD-76-11, NASA TMX-64988, NASA Marshall Space Flight Center, Ala., Mar 1976, 152 pp.

31. Bilbro, J.W. (1980) Atmospheric laser Doppler velocimetry: an overview, prepared for submission to Appl. Optics.

32. Lawrence, T.R., Wilson, D.J., Craven, C.E., Jones, I.P., Huffacker, R.M., and Thompson, J.A.L. (1972) A laser velocimeter for remote wind sensing, Rev. Sci. Inst. 43:512-518.

$$S/N = 0.25\ \eta N\beta\lambda A^2/B \tag{8}$$

where η is the detector quantum efficiency; N the scattering particle concentration; β the backscatter coefficient per particle; λ the laser wavelength; A^2 total light flux transmitted in photons/sec; and B the receiver bandwidth. The system spatial resolution along the beam axis ΔR was related to the telescope gain pattern. The half-power points were obtained as

$$\Delta R = 8\lambda Rf/\pi D^2 \tag{9}$$

where D was the telescope diameter; f the nominal range of focussing; and R the range for strong focussing or $R \simeq f$.

Hughes et al[33] conducted similar experiments with a CW CO_2 system. They point out that the CO_2 system is very good from the safety standpoint since the eye does not transmit or focus this IR radiation on the retina. Damage is caused only by burning, and this requires much higher power levels than are necessary to cause retina damage from a visual wavelength laser source.

In the United States, the American National Standards Institute[34] gives the relation for threshold safety for a focussed CO_2 laser beam as $0.56\ t^{[illegible]}\ J/cm^2$, where t is the exposure time and J the energy in Joules. The relation is considered valid for times ranging from 10^{-7} sec to 10 sec.

In the above experiments, Hughes, et al[33] used a 5 W CO_2 source and compared wind measurements from the laser and a Gill propellor anemometer. Data was acquired at 25 and 50 m ranges. The mean wind speed from the Gill data was 3.70 m sec^{-1} with variance 1.16, and the mean laser wind was 3.59 m sec^{-1}, with variance 0.92. Cross correlation coefficients of the wind time histories at 50 m was 0.90, rising to 0.95 at 25 m range.

A number of other comparison tests have been conducted in recent years. For example, Post et al[35] found in a CW laser test against R. M. Young propvane and three axis anemometers at about 150 m range that the correlation coefficients averaged 0.98 for 15 minute data runs. They concluded that the CO_2 laser provides an excellent remote wind sensing capability.

33. Hughes, A.J., O'Shaughnessy, J., Pike, E.R., McPherson, [illegible], C., and Clifton, T.H. (1972) Long range anemometry using a CO_2 laser, Opto-electronics 4:379-384.

34. American National Standard for Safe Use of Laser, American National Standards Institute Z-136.1, 1973, American National Standards Institute, Inc., New York, N.Y.

35. Post, M.J., Schwiesow, R.L., Cupp, R.E., Haugen, D.A., and Newman, J.T. (1978) A comparison of anemometer and lidar-sensed wind velocity data, J. Appl. Meteorol. 17:1179-1181.

Most of the atmospheric wind measurements to date have used a CW CO_2 laser operating in the Doppler backscatter mode. Several other types of interesting experiments have been conducted that have potential value. Benedette-Michelangeli, Congeduti, and Fiocco[36] used an argon ion laser in conjunction with a scanning Fabry-Perot interferometer to determine the peak backscatter from the aerosol Doppler return spectrum. Background noise was reduced through nighttime operation and use of an interference filter. Ranging was established by chopper modulation of the transmitted beam and appropriate gating of the photon counting detectors. A layer several hundred meters thick centered about 750 m above ground was studied. Good agreement with nearby rawinsonde data was obtained. They believed the system accuracy was to about ±0.3 m/sec, and could be improved.

Early experiments with FM-CW CO_2 lasers were reported by Honeycutt and Otto[37] and by Hughes, O'Shaughnessy, and Pike.[38] The latter authors illustrate aerosol backscatter, and point out that the Doppler velocity can be obtained from the deviations of ranging frequency. They obtained diffuse target data to 10 km range, and estimated attenuation effects in fog would limit operations to about the same as the visual range. The concept could provide a very attractive optical follow-on to the excellent work accomplished in recent years with FM-CW radar systems, and may provide an inexpensive answer to low elevation angle wind measurements at moderate ranges.

The use of pulsed CO_2 systems may permit an extension in measurement range. A system was developed by Jelalian, Keene, and Sonnenschein[39] for airborne study of clear air turbulence in a NASA sponsored research project. The equipment has recently been used in a surface measurement program for wind shear detection at Kennedy Space Center. Successful measurements on a thunderstorm gust front were reported by DiMarzio et al.[40] It is planned to modernize

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36. Benedette-Michelangeli, G., Congeduti, F., and Fiocco, G. (1972) Measurement of aerosol motion and wind velocity in the lower troposphere by Doppler optical radar, J. Atmos. Sci. 29:906-910.

37. Honeycutt, T.E., and Otto, W.F. (1972) FM-CW radar range measurements with a CO_2 laser, IEEE J. of Quant. Elect. QE-8:91-92.

38. Hughes, A.J., O'Shaughnessy, J., and Pike, E.R. (1972) FM-CW radar range measurement at 10 uM wavelength, IEEE J. of Quant. Elect. QE-8:909-910.

39. Jelalian, A.V., Keene, W.H., and Sonnenschein, C.M. (1972) Development of CO2 laser Doppler instrumentation for detection of clear air turbulence, Final Report, Raytheon Co. NAS8-24742, George C. Marshall Space Flight Center, NASA, Huntsville, Ala.

40. DiMarzio, C., Harris, C., Bilbro, J.W., Weaver, E.A., Burnham, D.C., and Hallock, J.W. (1979) Pulsed laser Doppler measurements of wind shear, Bull. Amer. Meteorol. Soc. 60:1061-1066.

the system and conduct flight measurements of the clear air wind patterns around thunderstorms. This effort has been described by Bilbro and Vaughan.[41]

The potential application of larger CO_2 systems to atmospheric measurements was indicated by Teoste and Capes.[42] They used the Firepond Lincoln Laboratory laser to obtain wind soundings to 8 km with an 0.5 m/sec accuracy. The VAD scan technique of Lhermitte and Atlas[43] was used to obtain averaged wind speed and direction at a number of altitudes.

Recent developments in gas laser technology have made it possible to consider use of higher power pulsed CO_2 lasers for long range atmospheric wind measurements. Two potential candidates are the UV pre-ionized transverse excited atmospheric (TEA) laser and the electron beam injection/laser injection TEA laser.

Huffaker et al[44] have recently issued a system design study for a possible shuttle or satellite-based TEA laser for use in global wind measurements. The analysis indicates that it would be feasible to employ orbits to 800 km and obtain an accuracy better than 2 m/sec^{-1} for tropospheric winds.

The technical characteristics and performance of one of the recently developed TEA lasers has been reported by Cruickshank.[45] He transmitted a peak power of 400 kw with total pulse energy of about 0.4 Joule. Ranges on natural targets such as tree-covered mountains were to 32 km on days of low attenuation. Under conditions of high relative humidity, the range decreased to about 16 km. He found that additional studies would be required to optimize the system optics, establish target reflectivity, and better characterize the atmospheric transmission losses.

A comprehensive review of factors affecting the design of ground-based laser wind systems has been conducted by Pratte et al[46] under sponsorship of the Army Electronics Command, Atmospheric Sciences Laboratory. An expression for signal to noise ratio was given based on Fresnel/Kirchoff calculations of system

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41. Bilbro, J.W., and Vaughan, W.W. (1978) Wind field measurement in the non-precipitous regions surrounding severe storms by an airborne pulsed Doppler lidar system, Bull. Amer. Meteorol. Soc. **59**:1095-1100.

42. Teoste, R., and Capes, R.N. (1978) High-altitude infrared radar wind measurements, J. Appl. Meteorol. **17**:1575-1578.

43. Lhermitte, R.M., and Atlas, D. (1961) Precipitation motion by pulse Doppler, Preprints Ninth Weather Radar Conf., Kansas City, Mo., Amer. Meteorol. Soc., 218-223.

44. Huffacker, R.M., Editor (1978) Feasibility study of Satellite-borne lidar global wind monitoring system, NOAA Tech. Memo. ERL WPL-37, Wave Propagation Laboratory, Boulder, Colo., 276 pp.

45. Cruickshank, J.M. (1979) Transversely excited atmospheric CO_2 laser radar with heterodyne detection, Appl. Optics **18**:290-293.

46. Pratte, F.J., Huffaker, R.M., Lawrence, T.R., and Loveland, R. (1979) System considerations of a long range coherent lidar wind sensor with particular emphasis on real weather effects, NOAA Tech. Memo. ERL WPL-42, Wave Propagation Laboratory, Boulder, Colo., 145 pp.

optical performance utilizing aerosol backscatter signals. Effects of atmospheric extinction and refractive turbulence are included. The results are expressed by the equation

$$SNR = \frac{\eta J \beta C \tau D^2 \exp(-2\alpha R)}{32h\nu [R^2(1 + a^2) + (\pi D^2/4\lambda)^2(1 - R/f)^2]} \tag{10}$$

This equation is an extension of the basic laser Eq. (2) given in Section 2.1. The nature of the $1/R^2$ range dependence has been expanded to include effects of optical refractive index fluctuations by the term $(1 + a^2)$ where $a^2 = D^2/4\, r_e^2$ and r_e = turbulence-limited effective optics radius, given by $r_e = 0.1048\lambda^{6/5} R^{-3/5}(C_N^2)^{-3/5}$. C_N^2 is the refractive index structure parameter.

The additional term $\pi D^2/4\lambda$ is associated with near-field effects of non-planar wavefronts at close range, and the term $(1 - R/f)$ is a focussing correction in the near-field.

Estimates of backscatter and extinction coefficients at 10.6 μm were summarized for fog conditions and for different cloud types. A β value of 10^{-3} km^{-1} was considered representative of good visibility conditions (23 km visual range). The range of β in the troposphere was taken from 10^{-1} km^{-1} to 10^{-5} km^{-1} for "clear air" conditions. For paths through fog or cloud values were estimated to range from 2×10^{-3} km^{-1} to 2.5 km^{-1}. The corresponding extinction coefficient α ranged from 0.1 km^{-1} to 100 km^{-1}.

They point out that very little actual scattering data is available to characterize cloud conditions at infrared frequencies, and that more extensive drop size distribution and thickness measurements are needed in conjunction with direct scattering experiments to improve on the rough estimates presently available. However, it appears that low clouds will generally be opaque to the IR beam, middle clouds will permit some beam penetration, and high clouds will generally permit wind measurements to be made through the cloud and beyond.

Parametric analysis of the SNR equation in terms of effects of various values of the scattering and extinction coefficients, and of optics diameter, indicated that useful wind measurements could usually be made to slant ranges of about 20 km in clear or moderately cloudy conditions where some holes in lower cloud decks were present. Optics diameters of about 0.5 m and laser pulse energy of 0.2 Joule were thought to be available. With some development, energies in the range from 1 to 5 Joules were believed attainable.

Kalafus[47] prepared a report on the utility and characteristics of laser measurements of terminal area wind shear. He concluded that a hybrid CW/pulsed TEA laser system would provide a capability of providing advance warning for all shear conditions of importance.

Review of the progress to date of the laser experiments described above and of the various design studies that have been conducted indicates that the CO_2 laser Doppler technique will be very valuable in future low level wind measurement programs, and that development of stable, more powerful laser sources for these measurements should be encouraged. AFGL has recently initiated such a program to assist in meeting Air Force requirements for low-level hazardous wind shear and wake vortex warnings.

3. CLEAR AIR RADAR TECHNIQUES

The extension of FM-CW radar techniques to obtain short range atmospheric measurements of the refractive index structure patterns was described by Richter.[48] The recent availability of a YIG tuned transistor oscillator that could be linearly shifted over a 200 Mhz frequency range centered on 2.9 Ghz provided a high-quality frequency ramp for the system. A minimum range of about 50 m was obtained with a range resolution of 1 m. Several time patterns of thin layers of refractive discontinuity at about 400 m height were shown to have wavelike characteristics, with a period of about 2 to 4 minutes and a 10 to 15 m peak-to-peak amplitude. The system was very sensitive, having a minimum discernable signal of about -150 dbm in contrast to normal weather radar sensitivities of about -110 dbm. The point target minimum cross section for this S band radar was about 3.7×10^{-6} cm^2 at 1 km. This is similar to the AN/TPQ-11 K band radar minimum cross section capability. It may be noted as a further indication of the sensitivity that most insects have a radar cross section greater than 10^{-2} cm^2. The radar reflectivity for distributed targets is defined as $\eta = \Sigma\sigma$ per volume. According to a formula in Atlas,[49] the minimum observable reflectivity is given as $\eta_{min} = 4.2 \times 10^{-15} \times r^2/h$, where r is the range in km and h is range resolution in meters. The result for 1 m resolution is $\eta_{min} = 4/2 \times 10^{-15}$ cm^{-1} at 1 km range.

47. Kalafus, R.M. (1978) Wind shear requirements and their application to laser systems, FAA-RD-77-123, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, 140 pp.

48. Richter, J.H. (1969) High resolution tropospheric radar sounding, Radio Science 4:1261-1268.

49. Atlas, D. (1964) Advances in radar meteorology, Advan. Geophys. 10:317-478.

The reflectivity measurements obtained with radars of this nature may be converted to measurements of the refractive index structure through application of turbulence theory. Ottersten[50] provides a concise summary of the theory and its development. It is found that $\eta(\lambda) \approx 0.38\, C_{n\lambda}^{2-1/3}$ where λ is the radar wavelength, and C_n^2 is the refractive structure constant.

An important advance in the FM-CW technique was the incorporation of methods for obtaining Doppler information from weak distributed targets. A technical discussion of the technique which employes spectral analysis of the signal from N sweeps was provided by Strauch and Chadwick.[51] The involved WPL group demonstrated it was possible through Doppler processing and range integration to obtain continuous range measurements of the wind field in the lower atmosphere through the motion of the clear air refractive index patterns. Chadwick, et al[52] describe the system used and show excellent agreement in the height profiles of wind measurements to 1 km with those obtained with a tethered balloon sounding system (Morris, et al[53]).

The impressive capabilities shown by the FM-CW system have led to further tests and development of improved antenna side-lobe suppression and enhanced frequency stability for extending system performance to lower elevation angles under AFGL sponsorship. Design studies and seasonal and diurnal measurements of C_n^2 have recently been summarized by Chadwick, et al.[54] Work on the application of the system to airport wind shear warning is continuing.

4. PASSIVE RADIOMETRIC SENSING

Remote sensing of temperature and moisture profiles or anomalies is based upon the utilization of radiometer data as input for estimates of solutions to the radiative transfer equation. Extensive work has been accomplished in the area of satellite-based sensors and related data analysis techniques. An excellent

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50. Ottersten, H. (1969) Radar backscattering from the turbulent clear atmosphere, Radio Science 4:1251-1255.

51. Strauch, R.G., and Chadwick, R.B. (1976) Measurement capabilities of FM-CW Doppler radars, Preprints 17th Radar Meteorol. Conf., Amer. Meteorol. Soc., 29-32.

52. Chadwick, R.B., Moran, K.P., Strauch, R.G., Morrison, G.E., and Campbell, W.C. (1976) Microwave radar wind measurements in the clear air, Radio Science 11:795-802.

53. Morris, A.L., Call, D.B., and McBeth, R.B. (1975) A small tethered balloon sounding system, Bull. Amer. Meteorol. Soc. 56:964-969.

54. Chadwick, R.B., Moran, K.P., and Campbell, W.C. (1979) Design of a wind shear detection radar for airports, IEEE Trans. on Geoscience Electronics GE-17:137-142.

review of the basic problems was presented by Wark and Fleming.[55] Elements of the problem are briefly reviewed in the following for reference to discussion of potentially useful ground or aircraft-based thermal or moisture anomaly detection.

The radiance available at a passive radiometer over the wave number interval from ν_1 to ν_2 is given by the radiative transfer equation

$$N(\mathrm{w\ cm^{-2}\ sr^{-1}}) = \int_{\nu_1}^{\nu_2} B(\nu, T_o)\phi(\nu)\tau_o \, d\nu - \int_{\nu_1}^{\nu_2} \int_{s} B(\nu, T)\phi(\nu)\partial\tau/\partial s \, ds \, d\nu \quad (11)$$

where s is the slant distance, τ the atmospheric transmittance, $\phi(\nu)$ a total system response function related to the filters used and the detector response, $B(\nu, T)$ the Planck function of frequency and temperature while T_o and τ_o represent a background source temperature and total path length transmittance respectively.

If scattering effects are disregarded, the transmittance may be written as

$$\tau_\nu(S) = \exp\left[-\frac{1}{R}\int_{o}^{s} \overline{K}(\Delta\nu)\,\frac{P}{T}\,Q\,ds\right] \quad (12)$$

where $\overline{K}(\Delta\nu)$ is a mean absorption coefficient for the constituent over the spectral band of interest, P is the atmospheric pressure, and Q is the mass mixing ratio of the absorbing gas.

Interpretation of the received radiometer data for determining the gas concentration or temperature as a function of range depends upon the effectiveness of the weighting function $\partial\tau_\nu/\partial s$, which is selected to allow for discrimination of the optical thickness or distance to the radiant phenomena of interest. Differentiation of τ_ν, on the assumption of constant T, P, Q over a distance increment S_i, yields

$$\partial\tau_\nu/\partial S = -\tau_\nu \overline{K}(\Delta\nu)PQ/RT \quad (13)$$

The background radiance associated with the first integral in Eq. (11) can be disregarded for some viewing situations. In this case, Eq. (11) reduces to

$$N = -\int_{\nu_1}^{\nu_2} \int_{o}^{s} B(\nu T)\phi(\nu)\partial\tau/\partial s \, ds \, d\nu \quad (14)$$

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55. Wark, D.Q., and Fleming, H.E. (1966) Indirect Measurements of Atmospheric temperature profiles from satellites, Mon. Wea. Rev. 94:351-362.

with the incorporation of Eq. (13), this becomes

$$N = \int_{\nu_1}^{\nu_2} \int_{o}^{s} B(\nu, T)\phi(\nu)\overline{K}(\Delta\nu)PQ/RT \exp\left[-\int_{o}^{s} \overline{K}(\Delta\nu)PQds/RT\right] \tag{15}$$

In this equation, one may be interested in obtaining best fits to the observed N by postulating distributions of T and/or P and Q as was done in the early astrophysical uses of the equation.

For satellite sounders, the first application was to deduce B(T), hence T(Z) given various spectral data bandwidths and the known atmospheric composition of the selected absorbing gas. A mean T, P distribution with height was taken to formulate the weighting functions expressed in Eq. (13).

If $B(\nu, T)$ is expanded and linearized for a small range in frequency, Eq. (15) becomes a Fredholm integral equation of the first kind. It can be written as

$$[N(s) - \beta(\nu)]/\alpha(\nu) = -\phi(\nu) \int_{o}^{s} B(\overline{\nu}, T)(s)K(\nu, s)\, ds \tag{16}$$

where $B(\nu, T) \equiv \alpha(\nu)B(\overline{\nu}, T) + \beta(\nu)$ as given by Elsasser[56] and Wark and Fleming.[55] $K(\nu, S)$ here represents the weighting function of Eq. (13).

Great care is needed to obtain meaningful temperature profile retrievals as solutions to this equation. Extensive mathematical and experimental efforts have been conducted to maximize the usefulness and accuracy of the solutions. A recent review of the problems involved was provided by Twomey.[57] In general, an accuracy of 1^{o} to 2^{o}K can be obtained in noncloudy fields of view. Discontinuities in the temperature profile are not resolved in sufficient detail for direct use in lower atmospheric profiling.

Instruments for temperature profiling have included equipment for measurement of energy received in the infrared, using the wings of the 15 μm CO_2 absorption band to provide weighting functions for various depths of atmosphere and multichannel microwave radiometers operating in the wings of the 60 Ghz oxygen absorption band. Even sharper absorption characteristics are obtainable near 118 Ghz.

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56. Elsasser, W.M. (1942) Heat transfer by infrared radiation in the atmosphere, Harvard Meteorological Studies No. 6, Harvard University Press, Cambridge, MA:107 pp.

57. Twomey, S. (1977) Introduction to the mathematics of inversion in remote sensing and indirect measurements, Elsevier Scientific Publishing Company, Amsterdam, Oxford, New York, 243 pp.

As an application of the foregoing, one may note the various efforts that were conducted in the 1960's, directed toward the remote detection of clear air turbulence. Infrared and microwave radiometers were suggested for employment on aircraft in attempts to determine the presence of distant temperature anomalies of a few degrees K that were believed related to turbulence zones.

An early example of equipment and the philosophy of measurement of a remote thermal discontinuity was presented by Astheimer.[58] Small scanning Fabry-Perot spectrometers were described that could scan over the range from 13 to 15 μm with 0.1 μM resolution.

Analysis of the variation of absorption coefficient with wavelength indicates near atmospheric transparency at 12 μM. However, the path length is reduced to a few hundred feet at 15 μM.

If the atmospheric path length is associated with N increments, Δs, each with a temperature difference ΔT_n from a reference temperature, and these differences are relatively small so that the Planck function can be linearized, one can assume that

$$N(\lambda) = \sum_{1}^{N} \Delta T_n e_{\Delta s} \tau_{sn}(\lambda) \qquad (17)$$

where $e_{\Delta s}$ is the emissivity of the increment Δs, and τ_{sn} is the transmissivity at wavelength λ over the path from the increment to the IR receiver. Then, if measurements at N wavelength are made, the set of simultaneous equations can be solved for the unknown ΔT_n values.

The pattern of the received signal intensity as a function of wavelength was shown as a set of curves with the parameter being the range to the thermal discontinuity. The plotted data indicate that as the discontinuity was approached, the signal amplitude increased, and the peak signal shifted toward longer wavelengths. The exact shape of the pattern depends upon the nature of the thermal anomaly.

Subsequent flight tests of IR systems produced some interesting results and a degree of correlation with turbulence encounters. Several practical problems were found in relation to aerodynamic heating of the sensor cover and the discovery of an exacting requirement for pitch stabilization, so that the normal temperature lapse rate with altitude would not be sensed as a horizontal anomaly when the aircraft deviated from level flight.

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58. Astheimer, R.W. (1964) An infrared technique for the remote detection of clear air turbulence, Proc. 3rd Symposium on Remote Sensing of Environment, 14-16 Oct 1964, Univ. of Michigan, Ann Arbor, Mich. (AD614032).

Improved understanding of the "jet upset" phenomena that had caused a number of aircraft accidents, and formulation of better procedures for handling aircraft in turbulence, has led to a lessening of support for research in this area in recent years. The status of the airborne sensor and measurements was fully described by Astheimer.[59]

Kuhn, et al[60, 61] have recently modified the technique by using IR radiometers to observe water vapor rotational bands. They sensed the high-altitude presence of increased vapor concentration associated with the crests of Kelvin-Helmholtz instability waves. These waves are often associated with clear air turbulence. A wavelength passband filter (S_rF_2) in the 26 to 35 μM region was found most suitable for detection of anomalies from 1.5 to 6 minutes prior to encountering turbulence. Of 194 encounters, 80 percent were said to have been predicted. The turbulence threshold was taken as 0.1g. Twelve percent of the warnings were false alarms, and in 8 percent of the cases, turbulence was encountered without an IR signal anomaly. Detection ranges of 70 to 100 km were estimated for high-altitude (9 km) measurements. These distances would reduce substantially at lower altitudes due to the increased atmospheric absorption.

A modification of this technique has been suggested by Caracena and Kuhn.[62] They believe that a dual looking IR radiometer operating in the CO_2 absorption region near 15 μM could be used to detect zones of cold air outflow such as are associated with gust fronts and downburst regions. One sensor was suggested to monitor the nearby IR temperature perpendicular to the flight path. This would be compared with the output of a sensor directed ahead of the aircraft. Weighting functions would be used to establish an effective range of around 10 km for this channel.

The temperature drop associated with downdraft phenomena has been related to vertical draft speeds by Foster[63] and to peak horizontal wind gusts near the surface of Fawbush and Miller.[64] More recently Hall et al[65] have described a relationship between the temperature drop and wind shear near the ground. Thus, a measurement of the temperature anomaly could be developed to establish general estimates of wind severity.

The possible effects of the background thermal pattern that might be encountered along the glidepath were not described by Caracera and Kuhn.[62] A recommended useful extension of this idea would be to test a surface-based rotating dual-channel IR system that would scan at a fairly low elevation angle. This system would measure anomalies in the thermal pattern as a function of azimuth, and provide an indication of possible downdraft and gust front activity in the area. It

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Because of the large number of references cited above, they will not be listed here. See References, page 29.

would be fairly inexpensive to implement such a test program for downdraft detection.

The second principal area of passive radiometric sensing utilizes a portion of the microwave spectrum. Meeks and Lilley[66] pointed out that the microwave emission from oxygen might be used to obtain satellite-based observations of the atmospheric temperature profile from around 40 km to the surface. Extensive development of the concept has led to satellite sounders for temperature and moisture profiling. Reports on the techniques and references have been reported by Waters et al[67] and Staelin et al.[68]

A variation of the technique suggested by Westwater[69] was to utilize a ground-based radiometer for measurements in the 10 to 100 Ghz spectral region. The data would be used for obtaining temperature profiles in the lower 10 km under cloud-free conditions. The basic technique is to estimate the temperature profile based on measurements of the oxygen emission expressed as a brightness temperature. Dicke-type radiometers using horn antennas can be used in the measurement. The single-frequency technique obtains a profile of brightness temperature as a function of elevation angle. The radiative transfer equation is then inverted to provide the temperature profile estimates. This technique suffers from differing amounts of sidelobe and backlobe energy being received as the elevation angle is changed.

An alternate technique was described by Snider[70] in which multiwavelength measurements were taken at a series of fixed elevation angles. Best results were obtained using four frequency measurements taken at a set of six elevation angles. Two frequency measurements were found to be almost as good and would represent a considerable simplification in equipment.

These techniques are useful in obtaining temperature profiles within the lower 5 or 6 km of the atmosphere. The nature of the exponential decay of the weighting

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66. Meeks, M.L. and Lilley, A.E. (1963) The microwave spectrum of oxygen in the earth's atmosphere, J. Geophys. Res. 68:1683-1703.

67. Waters, J.W., Kunzi, K.F., Pettyjohn, R.L., Poon, R.K.L., and Staelin, D.H. (1975) Remote sensing of atmospheric temperature profiles with the Nimbus-5 microwave spectrometer, J. Atmos. Sci. 32:1953-1969.

68. Staelin, D.H., Kunzi, K.F., Pettyjohn, R.L., Poon, R.K.L., and Wilcox, R.W. (1976) Remote sensing of atmospheric water vapor and liquid water with the Nimbus 5 microwave spectrometer, J. Appl. Meteorol. 15:1204-1214.

69. Westwater, E.R. (1965) Ground-based passive probing using the microwave spectrum of oxygen, Radio Science 69D:1201-1211.

70. Snider, J.B. (1972) Ground-based sensing of temperature profiles from angular and multi-spectral microwave emission measurements, J. Appl. Meteorol. 11:958-967.

functions used in connection with ground-based measurements degrades the accuracy at high levels.

Continuing efforts are being conducted at the NOAA Wave Propagation Laboratory to improve the detailed location and resolution of features such as thermal inversions. For example, Westwater[71] pointed out that a combination of active sounders such as acoustic or FM-CW radar probes and surface-based radiometry would produce better temperature profiles, since it is possible to use the locations of the profile inflection points to improve the mathematical inversion process.

The recent status of sounding for temperature and water vapor profiles has been described by Decker et al.[72] They described comparisons between ground-based microwave radiometer data taken with a Jet Propulsion Laboratory radiometer similar to the one used on the Nimbus 6 satellite to data from concurrent rawinsonde observations. Root-mean-square accuracies for the mean temperatures between the standard pressure levels to 500 mb ranged from 1 to $2^{o}K$. The water vapor profiles were in error by about three times the predicted error. These errors were thought to be due to radiosonde inaccuracy and to incomplete data on the water vapor absorption coefficients.

The foregoing programs are directed toward providing automated soundings for an ocean data buoy system and for possible use in the Prototype Regional Observing and Forecasting Service (PROFS). Efforts are continuing to provide improved instruments and analysis procedures for passive radiometric atmospheric profilers.

5. CONCLUSIONS

FM-CW radars and CO_2 laser Doppler Systems are likely to provide the best low-level wind shear information available from a ground-based sensor. The FM-CW clear air radar has been under development for a number of years. It is a very sensitive system and is capable of operation in clear weather or with cloud coverage. Limitations still exist in operation at very low elevation angles, such as the 3^{o} glide slope.

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71. Westwater, E.R. (1978) Improved determination of vertical temperature profiles of the atmosphere by a combination of radiometric and active ground-based remote sensors, Fourth Symposium on Meteorol. Obs. and Inst., 10-14 Apr. 1978, Amer. Meteorol. Soc., Boston, MA.

72. Decker, M.T., Westwater, E.R., and Guiraud, F.O. (1978) Experimental evaluation of ground-based microwave radiometric sensing of atmospheric temperature and water vapor profiles, J. Appl. Meteorol. 17:1788-1795.

Laser systems are still in the early development stage. High-resolution performance has been demonstrated to about 10 km range. Low elevation angle operation can be accomplished due to the very small beam divergence. A pulsed CO_2 system could be developed to have a useful range of around 20 km in the absence of lower clouds in the line of sight. The system would provide wind profile data, wind shear, and aircraft wake vortex detection functions in an airbase environment. The backscatter power as a function of range could be used to study the distribution and concentration of aerosols. This feature could provide valuable information for a variety of problems regarding applied optical sensor systems. Locations of temperature inversions and stable layers and information on air pollution movements also could be obtained. Passive IR sensors could be developed to test for low-altitude thermal anomalies associated with thunderstorm downdrafts. A rotating dual-channel system is envisaged. Deviations from a normal azimuthal pattern of energy received may provide a directional indication of downdraft activity. The magnitude of the anomaly could be related to the intensity of the outflow.

Work is continuing at the NOAA Environmental Research Laboratories on problems of obtaining temperature and humidity profiles from ground-based radiometric sensors. The best results are found when active sounders are added to locate significant levels of the inversions for incorporation in solutions of the radiation transfer equations.

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10. Hinkley, E.D., Ku, R.T., and Kelley, P.L. (1976) Techniques for detection of molecular pollutants by absorption of laser radiation, in Laser Monitoring of the Atmosphere, ed. E. D. Hinkley, Springer-Verlag, Berlin, Heidelberg, New York, 237-295.

11. Collis, R. T. H. (1966) Lidar: a new atmospheric probe, Quart. J. Roy. Meteorol. Soc. 92:220-230.

12. Koschmieder, H. (1924) Theorie der horizontalen sichtweite, Beitr. Phys, Frei. Atmos. 12:35-55 and 171-181.

13. Smithsonian Meteorological Tables, 6th Ed., ed. R. J. List, Smithsonian Institution, Wash., D.C., 527 pp.

14. Middleton, W.E.K. (1958) Vision Through the Atmosphere, Univ. of Toronto Press, 246 pp.

15. Pueschell, R.F. and Noll, K.E. (1967) Visibility and aerosol size frequency distribution, J. Appl. Meteorol. 6:1045-1052.

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